The Structure and Thickness of Europa's Ice Shell

What we think we know, and what we hope to learn from the Europa Clipper

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Accessing the Subsurface of Ocean Worlds
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The thickness of Europa’s ice shell has been the subject of intense debate – estimates range from a few km to ~30 km.
Temperature structure

Mitri and Showman, 2005
Galileo coverage of Europa

Resolution
(km/pixel)

Very High
(0-0.1)

Regional
(0.1-0.5)

Large-scale
(0.5-1)

Global
(1-20)

Europa
< 0.5%

13.5%

24.5%

60.8%
Europa’s surface shows evidence for two major styles of deformation.
Europa’s eccentric orbit

- For an eccentric satellite orbit, permanent bulge faces empty focus
- Radial tide of $\sim 30$ m for Europa if ice shell is decoupled by ocean
- Tidal bulge librates to face Jupiter’s center of mass
- Tidal deformation dissipates energy $\Rightarrow$ tidal heating
- Misaligned tidal bulge and ice thickness variations promote nonsynchronous rotation

$P = 85$ hr $e = 0.01$

[after Nash et al., 1982]
Diurnal stresses

0° to 180°

Tension
Compression

0.2 MPa
Non-synchronous rotation

Analysis of the orientation and distribution of surface lineaments and correlation to past stress fields by Geissler et al. (1998) suggests that Europa spins faster than the synchronous rate, or did so in the past.

However, analysis of lineament azimuths in Europa’s Bright Plains region by Rhoden and Hurford (2013) suggests ~1° of forced obliquity and little support for non-synchronous rotation.

Geissler et al. (1998)

Rhoden and Hurford (2013)

[Ojakangas & Stevenson, 1989]
Ridges

- Background ridged plains
- Complex ridges
- Double ridges
- Troughs

Types of ridges:
1. Isolated Trough
2. Raised-Flank Trough
3. Double Ridge
4. Triple Ridge
5. Medial Trough
6. Complex Ridge
Ridge formation models

- Double ridges: extrusion or intrusion of water or warm ice
- Shear heating from strike-slip motion along fractures could warm and melt ice
- Ridge origin models have different implications for ocean communication

*Greenberg et al., 1998; Pappalardo et al., 1998*
Cycloidal fractures are explained by time-varying diurnal stresses.

Ocean is necessary for sufficient tidal amplitude and stress.

[Hoppa et al., 1999]
Small-Circle Depressions

AKA Crop circles

Broad arcuate regional-scale troughs and depressions on Europa do not fit current diurnal or proposed NSR stresses (Schenk et al., 2008)
Troughs can be matched with stresses predicted by an episode of $80^\circ$ of true polar wander.

Schenk et al., 2008
Pull-apart bands: Evidence of a mobile lithosphere
Pull-apart bands
High-standing topography, bilateral symmetry, and similarities in interior morphologies suggest a similar formation mechanism to terrestrial mid-ocean ridges, with band morphology a function of spreading rate.

New modeling by Howell and Pappalardo (2017) suggests that differences in band morphology may be a function of lithospheric strength at the time of formation.
Accommodation of extension may be via subduction.

Kattenhorn and Prockter, 2014
Plates would be subsumed below the brittle ice layer (few km) into the warmer subsurface portion of the ice shell
Castalia Macula

Low-albedo depression between two significantly disrupted uplifted domes
Northern dome = 900 m above surrounding ridged plains
Southern dome = 750 m
Castalia Macula = -350 m
Total topographic amplitude = 1250 m
Lenticulae
AKA pits, spots and domes
Lenticulae

Pappalardo et al., 1999
Convection in Europa's Ice Shell

- Chaos and lenticulae suggest convection of ice shell
- Ice shell can convect for small grain sizes (~1 mm), if tidally strained
- Warm (~240 K) plumes rise from base of ice in ~10^5 yr
- Compositional buoyancy needed to breach near-surface “stagnant lid”
~78% of the plates in Conamara have undergone horizontal translations, and 81% have rotated by on average 11°, implying elevated near-surface temperatures and a highly mobile substrate over lateral scales of ~ 100 km.
Chaos endmember models

liquid water

partial melt

warm ice

Melting model

Diapirism model
Candidate chaotic terrain formation models

Melt-through

Diapirism

Brine-mobilization driven by diapirism

Brine-mobilization driven by partial melt-through

Sill formation

Impact

Collins and Nimmo, 2007
Candidate chaotic terrain formation models

- Melt-through
- Diapirism
- Brine-mobilization driven by diapirism
- Brine-mobilization driven by partial melt-through
- Sill formation
- Impact

Colllins and Nimmo, 2007
Using terrestrial analogs, Schmidt et al. (2011) showed that chaos matrix domes and depressions can be explained if they form above shallow subsurface (~3 km) lakes.
Pit and uplift modeling

- Modeling of saucer-shaped sills by Manga and Michaut (2016) explains the features of pits, spots, and domes, and suggests that intrusions are, or were 1-5 km below the surface.
- Liquid water is predicted to exist presently under pits.
Ice thickness estimates using impact features

Moore et al., 2001

All impact features on Europa > 4 km in diameter

Moore et al., 2001
Impact Structures

- Few large impact craters imply 40–90 Myr old surface
- Central peak craters show “relaxed” topography
- Multi-ringed impacts penetrated thick ice

\[ D_c \sim 30 \text{ km} \implies d_t \sim 20 \text{ km} \]

[Schenk, 2002]

After McKinnon & Melosh [1980]
Large impacts

• Different basin morphologies are predicted depending on the thickness of the upper layer

• Ice thicknesses of >12-16 km are consistent with the formation of ring faults around craters like Tyre and Callanish (Turtle (1998))
Central peak craters

- The transient crater diameter of Pwyll, one of Europa’s youngest craters, is estimated to be ~16 km, implying that Europa’s ice shell was at least 15 km thick when Pwyll formed.

- Pwyll is nevertheless quite shallow, with a subdued floor. This small depth-to-diameter ratio may be due to the isostatic adjustment of large-scale topography facilitated by warm, plastically deformable ice at depth.
What can Europa’s putative plumes tell us about the thickness of the shell?

- Hubble has observed hydrogen and oxygen ultraviolet glow, 200 km above Europa.
- Indicates water plumes.
- May be transient, perhaps linked to Europa's tidal cycle.
- Source may be the ocean (although unlikely if shell is thick), a lake within the ice, or perhaps warm shallow ice.

Hydrogen glow

NASA/L. Roth

Artist’s depiction
# Ice shell thickness estimates: Mechanical - flexure

<table>
<thead>
<tr>
<th>Citation</th>
<th>Model method</th>
<th>Location</th>
<th>Ice shell estimated thickness</th>
<th>Portion of shell modeled</th>
<th>Method assumptions and notes</th>
<th>Application to Androgeos Linea*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Billings and Kattenhorn (this paper)</td>
<td>Flexure, line load</td>
<td>41.7° N, 273.4° W Androgeos Linea</td>
<td>520–2410 m</td>
<td>Elastic</td>
<td>Measured distance to maximum stress location (flanking cracks). Broken plate model. ( E = 6 \times 10^5 – 6 \times 10^6 , \text{Pa} ), ( \nu = 0.3 ), ( \rho_0 = 1186 , \text{kg/m}^3 ), ( g = 1.35 , \text{m/s}^2 ).</td>
<td>520 m (for highest ( E ) value)</td>
</tr>
<tr>
<td>Billings and Kattenhorn (this paper)</td>
<td>Flexure, line load</td>
<td>8.4° N, 271° W Ridge R</td>
<td>216–1000 m</td>
<td>Elastic</td>
<td>As above.</td>
<td>520 m</td>
</tr>
<tr>
<td>Billings and Kattenhorn (this paper)</td>
<td>Flexure, line load</td>
<td>47° N, 325.7° W Ridge C2r</td>
<td>465–2160 m</td>
<td>Elastic</td>
<td>As above.</td>
<td>520 m</td>
</tr>
<tr>
<td>Chuang et al. (2001)</td>
<td>Flexure, line load</td>
<td>22° N, 82° W SW quadrant of Munias Chaos</td>
<td>~2.1–2.6 km</td>
<td>Elastic</td>
<td>Determined distance to forebulge by fitting model to topography. ( E = 9.33 , \text{GPa}, \nu = 0.325 ), ( \rho_0 = 1208 , \text{kg/m}^3 ). Fit model to topography. ( E = 9 , \text{GPa}, \nu = 0.325 ), ( \rho_0 = 1208 , \text{kg/m}^3 ).</td>
<td>449 m</td>
</tr>
<tr>
<td>Figueredo et al. (2002)</td>
<td>Flexure, cylindrical load on sphere</td>
<td>22° N, 82° W SW quadrant of Munias Chaos</td>
<td>~4 ± 2 km</td>
<td>Elastic</td>
<td></td>
<td>454 m</td>
</tr>
<tr>
<td>Hurford et al. (2004)</td>
<td>Flexure, line load</td>
<td>Various ridges</td>
<td>~100–400 m</td>
<td>Elastic</td>
<td>Measured distances to forebulge using photoclinimetry. Broken plate model. ( E = 1 , \text{GPa}, \rho_0 = 1055 , \text{kg/m}^3 ), ( g = 1.35 , \text{m/s}^2 ).</td>
<td>908 m</td>
</tr>
<tr>
<td>Nimmo et al. (2003)</td>
<td>Flexure, distributed load</td>
<td>3° N, 182° W Gilix</td>
<td>6 km</td>
<td>Elastic</td>
<td>Measured forebulge distance using stereoscopic data. Fit model to topography. Continuous plate model. ( E = 1 , \text{GPa}, \rho_0 = 900 , \text{kg/m}^3 ).</td>
<td>861 m; 342 m cont.</td>
</tr>
<tr>
<td>Tufts (1998)</td>
<td>Flexure, line load</td>
<td>8.4° N, 271.3° W Ridge R</td>
<td>123–353 m</td>
<td>Elastic</td>
<td>Measured distance to forebulge based on the distortion of cross-cutting surface features. Broken plate model. ( E = 1–24 , \text{GPa}, \nu = 0.33 ), ( \rho_0 = 920 , \text{kg/m}^3 ), ( g = 1.3 , \text{m/s}^2 ).</td>
<td>295 m</td>
</tr>
<tr>
<td>Williams and Greeley (1998)</td>
<td>Flexure, line load</td>
<td>W of Conamara in smooth band</td>
<td>150–500 m</td>
<td>Elastic</td>
<td>Measured forebulge distance from photoclinimetry. Continuous plate model. ( \rho_{liq} = 1186 , \text{kg/m}^3 ), ( E ) on higher end of range of ( 6 \times 10^5 – 6 \times 10^6 , \text{Pa} ), ( \nu = 0.3 ), ( g = 1.35 , \text{m/s}^2 ).</td>
<td>520 m; 206 m cont.</td>
</tr>
<tr>
<td>Williams and Greeley (1998)</td>
<td>Flexure, distributed load</td>
<td>W of Conamara in smooth band</td>
<td>100–350 m</td>
<td>Elastic</td>
<td>( \rho_{liq} = 1186 , \text{kg/m}^3 ), ( \rho_{ice} = 1126 ), ( \rho_{load} = 1510 ). ( E ) on higher end of range of ( 6 \times 10^5 – 6 \times 10^6 , \text{Pa} ), ( \nu = 0.3 ), ( g = 1.35 , \text{m/s}^2 ).</td>
<td>520 m; 206 m cont.</td>
</tr>
</tbody>
</table>

* Re-calculated ice thickness at Androgeos Linea using values for \( E, \nu, \rho_0, \) and \( g \), if provided, by the cited researcher. If a range in \( E \) was cited, only the high end of the range was used; when no value was given for a parameter, values were used from Billings and Kattenhorn. A broken plate model was used for comparison calculations; in addition, a continuous plate model result was calculated where also used by the original researcher.
## Ice shell thickness estimates: Mechanical - non-flexure

<table>
<thead>
<tr>
<th>Citation</th>
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<th>Ice shell estimated thickness</th>
<th>Portion of shell modeled</th>
<th>Method assumptions and notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carr et al. (1998)</td>
<td>Buoyancy</td>
<td>13° N, 273° W Conamara</td>
<td>≥2 km</td>
<td>Total</td>
<td>Results are the minimum thickness if rafts are floating in liquid water. No input values given.</td>
</tr>
<tr>
<td>Carr et al. (1998)</td>
<td>Dimension of chaos rafts</td>
<td>13° N, 273° W Conamara</td>
<td>≤“Few km”</td>
<td>Brittle</td>
<td>Thickness is probably ≤ horizontal dimensions of smallest plates that retain original surface features. Lower limit from observation of rotation of blocks; upper limit is from available driving stress to overcome lithostat.</td>
</tr>
<tr>
<td>Golombek and Banerdt (1990)</td>
<td>Structural integrity of undeformed, mobile ice rafts</td>
<td>Anti-jovian, Wedges region</td>
<td>3–6 km</td>
<td>Brittle</td>
<td>Used “plate dimensions”.</td>
</tr>
<tr>
<td>Greeley et al. (1998)</td>
<td>Structural integrity of undeformed, mobile ice rafts</td>
<td>Unspecified</td>
<td>≤“Few km”</td>
<td>Total</td>
<td>Cracks penetrate to liquid and are caused by tidal stresses.</td>
</tr>
<tr>
<td>Greenberg et al. (2000)</td>
<td>Lithostatic stress constraints</td>
<td>Global</td>
<td>≤“Few km”</td>
<td>Total = brittle</td>
<td>Cycloidal cracks penetrate to liquid and are caused by tidal stresses. Water ice shear mod. $\mu = 3.52$ GPa; $v = 0.33$; distal stress $\sigma_{\text{max}} = 40$ kPa.</td>
</tr>
<tr>
<td>Hoppa et al. (1999a)</td>
<td>Lithostatic stress constraints</td>
<td>Global</td>
<td>≤“Few km”</td>
<td>Total = brittle</td>
<td>Raft height $h = 240–290$ m. Briny ice in briny liquid, $\rho_{\text{ice}} = 927$ (pure water ice) to 1126 kg/m$^3$ (briny ice); $\rho_{\text{liq}} = 1186$ kg/m$^3$ (briny liquid).</td>
</tr>
<tr>
<td>Kadel et al. (2000)</td>
<td>Buoyancy (isostacy of rafts in liquid)</td>
<td>34° N, 144° W khaos at Tyre</td>
<td>0.9–5.5 km</td>
<td>Total</td>
<td>Raft height $h_{\text{ave}} = 106$ m for chaos features in latitude range. Other parameters as above.</td>
</tr>
<tr>
<td>Kadel and Greeley (2000)</td>
<td>Buoyancy (isostacy of rafts in liquid)</td>
<td>16.44° N–10° N 11 rafts</td>
<td>2.10 km</td>
<td>Total</td>
<td>Raft height $h_{\text{ave}} = 120$ m for chaos features in latitude range. Other parameters as above.</td>
</tr>
<tr>
<td>Kadel and Greeley (2000)</td>
<td>Buoyancy (isostacy of rafts in liquid)</td>
<td>0° N–10° N 60 rafts</td>
<td>1.27 km</td>
<td>Total</td>
<td>Raft height $h_{\text{ave}} = 184$ m for chaos features in latitude range. Other parameters as above.</td>
</tr>
<tr>
<td>Kadel and Greeley (2000)</td>
<td>Buoyancy (isostacy of rafts in liquid)</td>
<td>10° N–20° N 6 rafts</td>
<td>3.64 km</td>
<td>Total</td>
<td>Raft height $h_{\text{ave}} = 296$ m for chaos features in latitude range. Other parameters as above.</td>
</tr>
<tr>
<td>Kadel and Greeley (2000)</td>
<td>Buoyancy (isostacy of rafts in liquid)</td>
<td>20° N–30° N 13 rafts</td>
<td>5.85 km</td>
<td>Total</td>
<td>Raft height $h_{\text{ave}} = 217$ m for chaos features in latitude range. Other parameters as above.</td>
</tr>
<tr>
<td>Kadel and Greeley (2000)</td>
<td>Buoyancy (isostacy of rafts in liquid)</td>
<td>30° N–40° N 18 rafts</td>
<td>4.29 km</td>
<td>Total</td>
<td>Raft height $h_{\text{ave}} = 299$ m for chaos features in latitude range. Other parameters as above.</td>
</tr>
<tr>
<td>Schenk and McKinnon (1989)</td>
<td>Structural integrity of undeformed, mobile ice rafts/lithostatic stress constraints</td>
<td>Anti-jovian, Wedges region</td>
<td>“A few” - 10 km</td>
<td>Brittle</td>
<td></td>
</tr>
<tr>
<td>Williams and Greeley (1998)</td>
<td>Buoyancy (isostacy of blocks in liquid)</td>
<td>13° N, 273° W Conamara</td>
<td>0.8–2.9 km</td>
<td>Total</td>
<td>Block height $h = 40–150$ km. Briny ice in briny liquid, $\rho_{\text{ice}} = 1126$ kg/m$^3$, $\rho_{\text{liq}} = 1186$ kg/m$^3$.</td>
</tr>
</tbody>
</table>
# Ice shell thickness estimates: Impact cratering

<table>
<thead>
<tr>
<th>Citation</th>
<th>Model method</th>
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<th>Ice shell estimated thickness</th>
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</thead>
<tbody>
<tr>
<td>Greeley et al. (1998)</td>
<td>Transient crater depth, crater morphology</td>
<td>25° S, 271° W Pwyll</td>
<td>≥10–15 km</td>
<td>Total</td>
<td>Based on the calculated transient crater depth and the observation of crater morphology (including central peaks), implying that the impactor did not penetrate the ice shell.</td>
</tr>
<tr>
<td>Kadel et al. (2000)</td>
<td>Scaling of transient crater depth based on diameter</td>
<td>34° N, 144° W Tyre</td>
<td>3.5 ± 0.5 km</td>
<td>Total</td>
<td>Impactor penetrated to fluid layer.</td>
</tr>
<tr>
<td>Moore et al. (1998)</td>
<td>Impact modeling and crater morphology</td>
<td>Callanish, Tyre</td>
<td>~6–15 km</td>
<td>Total</td>
<td>Ice layer overlies low-viscosity layer. Impactor penetrated the ice layer and radial stresses in top layer caused fracturing in concentric rings around impact site.</td>
</tr>
<tr>
<td>Moore et al. (1998)</td>
<td>Impact modeling and crater morphology</td>
<td>Pwyll</td>
<td>~10–15 km</td>
<td>Total</td>
<td>Ice layer overlies low-viscosity layer. Impactor did not penetrate the ice layer.</td>
</tr>
<tr>
<td>Moore et al. (2001)</td>
<td>Transient crater depth/morphology</td>
<td>2° S, 180° W Gilix</td>
<td>≥2.4–4.7 km</td>
<td>Total</td>
<td>Based on the calculated transient crater depth and the observation of a central peak complex, implying that the impactor did not penetrate the ice shell.</td>
</tr>
<tr>
<td>Moore et al. (2001)</td>
<td>Transient crater depth/morphology</td>
<td>3° N, 240° W Manannán</td>
<td>≥2.86–5.47 km</td>
<td>Total</td>
<td>Based on the calculated transient crater depth and the observation of interior massifs, implying that the impactor did not penetrate the ice shell.</td>
</tr>
<tr>
<td>Moore et al. (2001)</td>
<td>Transient crater depth/morphology</td>
<td>34° N, 146° W Tyre</td>
<td>≥5.59–9.98 km</td>
<td>Total</td>
<td>Based on the calculated transient crater depth and the observation of crater morphology (including no central peaks), implying that the impactor did penetrate the ice shell.</td>
</tr>
<tr>
<td>Moore et al. (2001)</td>
<td>Transient crater depth/morphology</td>
<td>25° S, 271° W Pwyll</td>
<td>≥2.6–3.6 km</td>
<td>Total</td>
<td>Based on the calculated transient crater depth and the observation of crater morphology (including central peaks), implying that the impactor did not penetrate the ice shell.</td>
</tr>
<tr>
<td>Schenk (2002)</td>
<td>Crater morphology</td>
<td>Global</td>
<td>19 km</td>
<td>Total</td>
<td>Results are a lower boundary. Morphology variations are due to depth of penetration through the total ice layer. Calculated transient crater depth based on crater diameter.</td>
</tr>
<tr>
<td>Turtle and Pierazzo (2001)</td>
<td>Impact modeling and crater morphology</td>
<td>Numerous impact sites</td>
<td>&gt;3–4 km</td>
<td>Total</td>
<td>Model is for ice layer over water. Results are a lower boundary. The transient crater diameter is estimated from the observed final crater diameter. As above.</td>
</tr>
<tr>
<td>Turtle and Ivanov (2002)</td>
<td>Impact modeling and crater morphology</td>
<td>Various small complex craters</td>
<td>≥5–7 km</td>
<td>Total</td>
<td>As above.</td>
</tr>
<tr>
<td>Turtle and Ivanov (2002)</td>
<td>Impact modeling and crater morphology</td>
<td>Various large complex craters</td>
<td>≥12–18.5 km</td>
<td>Total</td>
<td>As above.</td>
</tr>
</tbody>
</table>
## Ice shell thickness estimates: Thermodynamic analyses

<table>
<thead>
<tr>
<th>Citation</th>
<th>Model method</th>
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<th>Ice shell estimated thickness</th>
<th>Portion of shell modeled</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Hussmann et al. (2002)</td>
<td>Thermal equilibrium</td>
<td>Global</td>
<td>~32–38 km</td>
<td>Total</td>
<td>Calculates equilibrium thickness for tidal dissipation assuming a Maxwell rheology in a convecting ice layer that is overlain by a conducting stagnant lid and elastic layer. Implies a heat flow of ~20 mW/m² and a melting point viscosity of ~10^{13}–10^{14} Pa s. Constraints thickness for convection to occur. Applies temperature-dependent viscosity convection scaling. Shell assumed to be pure water ice. Shows convection is possible for ice shells &lt;30 km thick. Presumes that shell thinning and thermal runaways could occur if convecting, tidally heated shell exists. Based on elastic thickness of 6 km from flexural analysis, $E = 1$ GPa, $\rho_0 = 900$ kg/m³. Convecting ice layer underlies brittle layer.</td>
</tr>
<tr>
<td>Nimmo et al. (2003)</td>
<td>Temperature gradient through ice shell</td>
<td>3° N, 182° W Cilix</td>
<td>15 km</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Ojakangas and Stevenson (1989)</td>
<td>Thermal equilibrium</td>
<td>Global (averages)</td>
<td>13–25 km</td>
<td>Total</td>
<td>Range includes calculations using both Maxwell and generalized heat flow rheologies. Applies a parameterized convection approach to constrain the thickness of a convecting layer, to which a &lt;2 km thick conductive lid is added. Results are thickness at which convection can initiate. Dome features are caused by diapirs and size is related to diapir size; size of domes limits depths from which diapirs can originate. Range is geographic, from equator to poles. Uses a Maxwell rheology. Both tidal and radiogenic heating contribute.</td>
</tr>
<tr>
<td>Pappalardo et al. (1998)</td>
<td>Initiation of convection</td>
<td>Global</td>
<td>~3–10 km</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Rathburn et al. (1998)</td>
<td>Convection and diapirs</td>
<td>15° N, 270° W Conamara Chaos</td>
<td>&lt;“Few tens of km”</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Sotin et al. (2004)</td>
<td>Thermal equilibrium</td>
<td>Global</td>
<td>17–29 km</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Nimmo (2004b)</td>
<td>Force balance during rifting</td>
<td>Global</td>
<td>&lt;15 km</td>
<td>Total</td>
<td>Utilized a technique developed for terrestrial rift modeling. Assumed a constant strain rate and a conducting shell.</td>
</tr>
<tr>
<td>Pappalardo et al. (1999)</td>
<td>Terrestrial analog approach</td>
<td>8.4° N, 271.3° W</td>
<td>1–2 km</td>
<td>Brittle (seismic)</td>
<td>On earth, effective elastic lithospheric thickness = 20–40% of actual (seismic) thickness of brittle lithosphere due to weakening by faults; effective elastic thickness = ~400 m. Assumes elastic thickness = 10–50% of the total lithospheric thickness based on terrestrial analogy.</td>
</tr>
<tr>
<td>Tufts (1998)</td>
<td>Terrestrial analog approach</td>
<td>8.4° N, 271.3° W Ridge R</td>
<td>0.25–3.5 km</td>
<td>Total</td>
<td></td>
</tr>
</tbody>
</table>

*Billings and Kattenhorn, 2005*
Europa Mission Concept
A capable solar-powered spacecraft carrying ten science experiments

- 16 m radar HF antenna (2x)
- Magnetometer boom (5 m)
- Solar panels (8x) 2.2 m x 4.1 m each
- Forward-pointed instruments
- Downward-pointed instruments
- Radar VHF antenna (4x)
- Spacecraft height: 4.6 m
- Solar array width: 22.3 m
Mission concept

- Launch 2022, arrive as early as 2025
- 3-year primary mission, includes >42 encounters with Europa
- Multiple flybys of Europa build up global-regional coverage while minimizing radiation dose
Europa Multiple-Flyby Mission
Science Goal and Objectives

**Goal:** Explore Europa to investigate its habitability

**Objectives:**

- **Ice Shell and Ocean:** Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange

- **Composition:** Understand the habitability of Europa's ocean through composition and chemistry

- **Geology:** Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities
NASA-Selected Europa Instruments

- **MASPEX** Mass Spectrometer
  - Sniffing atmospheric composition

- **SUDA** Dust Analyzer
  - Surface & plume composition

- **ICEMAG** Magnetometer
  - Sensing ocean properties

- **PIMS** Faraday Cups
  - Plasma environment

- **EIS** Narrow-Angle Camera + Wide-Angle Camera
  - Mapping alien landscape in 3D & color

- **E-THENIS** Thermal Imager
  - Searching for hot spots

- **MISE** IR Spectrometer
  - Surface chemical fingerprints

- **REASON** Ice-Penetrating Radar
  - Plumbing the ice shell

- **Gravity Science Working Group**
  - Confirming an ocean

Legend:
- **Remote Sensing**
- **In Situ**
Most relevant for measuring ice shell structure and processes
Europa Imaging System (EIS)
Zibi Turtle, Johns Hopkins U. Applied Physics Laboratory (APL)

• Constrain the formation of surface features and potential for current activity
• Characterize the ice shell
• Characterize the surface regolith at small scales

• NAC: high-resolution, stereo imaging, color
• NAC gimbal permits independent targeting, enabling near-global mapping, including stereo, and high-phase observations to search for potential plumes
• WAC: along-track stereo and color context imaging
• WAC supports cross-track clutter characterization for ice-penetrating radar

<table>
<thead>
<tr>
<th>Key Instrument Parameters</th>
<th>NAC</th>
<th>WAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector</td>
<td>4096 × 2048 rad-hard CMOS</td>
<td></td>
</tr>
<tr>
<td>Wavelength Range</td>
<td>Panchromatic plus 6 filters (350 – 1050 nm)</td>
<td></td>
</tr>
<tr>
<td>Instantaneous Field of View</td>
<td>10 μrad (0.5 m/pixel at 50 km)</td>
<td>218 μrad (11 m/pixel at 50 km)</td>
</tr>
<tr>
<td>Field of View</td>
<td>2.347° × 1.173°</td>
<td>48° × 24°</td>
</tr>
<tr>
<td>TDI</td>
<td>Typically ≤18 lines of Time Delay Integration</td>
<td></td>
</tr>
</tbody>
</table>
Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)
Don Blankenship, University of Texas Institute for Geophysics, Austin

- Characterize the distribution of any shallow subsurface water
- Search for an ice-ocean interface and characterize the ice shell’s global thermophysical structure
- Investigate the processes governing material exchange among the ocean, ice shell, surface, and atmosphere
- Constrain the amplitude and phase of the tides
- Characterize scientifically compelling sites, and hazards, for a potential future landed mission

Simultaneous high-resolution shallow sounding, altimetry, and reflectometry, along with lower resolution, full depth sounding of the ice shell and plasma measurements

<table>
<thead>
<tr>
<th>Key instrument Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dual Frequencies</strong></td>
</tr>
<tr>
<td>60 MHz ((\lambda = 5) m) Very High Frequency (VHF) globally, and 9 MHz ((\lambda = 33.3) m) High Frequency (HF) anti-Jovian</td>
</tr>
<tr>
<td><strong>Vertical Resolution</strong></td>
</tr>
<tr>
<td><em>Shallow sounding</em>: VHF with &lt;15 m resolution from depths of 300 m to 3 km; <em>Deep sounding</em>: VHF or HF with &lt;150 m resolution from depths of 1 km to 30 km; <em>Altimetry</em>: VHF with &lt;15 m resolution</td>
</tr>
<tr>
<td><strong>Antenna</strong></td>
</tr>
<tr>
<td>2 deployable HF and 4 VHF dipole antennas mounted on solar array</td>
</tr>
<tr>
<td><strong>Radiated Power</strong></td>
</tr>
<tr>
<td>10-30 W</td>
</tr>
</tbody>
</table>
Europa Thermal Imaging System (E-THEMIS)
Philip Christensen, Arizona State University

- Detect and characterize thermal anomalies that may indicate recent activity
- Identify active plumes
- Determine the regolith particle size, block abundance and subsurface layering for surface process studies

Key instrument Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filters</td>
<td>7–14, 14–28, 28–70 μm</td>
</tr>
<tr>
<td>Resolution</td>
<td>5 – 35 m at 25 km range</td>
</tr>
<tr>
<td>Image width</td>
<td>5.7° cross-track (720 pixels)</td>
</tr>
<tr>
<td>Radiometric Precision</td>
<td>1 K for global-scale observations; 2 K for local-scale observations</td>
</tr>
<tr>
<td>Radiometric accuracy</td>
<td>1.25%</td>
</tr>
<tr>
<td>Time Delay Integration</td>
<td>16 lines</td>
</tr>
</tbody>
</table>
• Characterize Europa’s time-varying gravitational tides ($k_2$)
• Confirm the existence of Europa’s subsurface ocean
• In combination with radar altimetry ($h_2$), constrain ice shell thickness

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Key Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>4 - 10 dB-Hz min @D/L</td>
</tr>
<tr>
<td>Fanbeam FOV</td>
<td>±15° by ±50°</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.07 mm s$^{-1}$ (60 s integration time)</td>
</tr>
</tbody>
</table>

Three Fixed Fanbeam (FB) antennas, plus utilizes two low-gain antennas (LGAs) to fill in coverage esp. for high-latitude fly-bys
• X-band up & down
• Radio Science Receivers used at DSN
• Opportunities for arraying DSN antennas and augmenting DSN with ESA antennas
• Non-intrusive with the suite of science instruments during flyby
Comprehensive Surface Coverage

Ground tracks permit globally distributed regional coverage

- Above 1,000 km: 2
- 250 km to 750 km: 6
- 80 km to 100 km: 9
- 50 km: 18
- 25 km: 10
Hypothetical example from the Jupiter Europa Orbiter mission study using geophysical techniques

EJSM final report, 2010
Europa Lander
Comparison of Europa’s surface age with terrestrial bodies

Doggett et al., 2007
Cyclical Geological Activity?

- Mapping suggests geological changes:
  - Transition from ridged plains to chaos; waning activity
- Strange for a surface just ~40–90 Myr old
- Tidal heating and orbital evolution of the 3 resonant Galilean satellites are linked:
  - Possible cyclical tidal heating & geological activity

[Figueredo & Greeley, 2004]

Coupled orbits

Europa ice thickness

[Hussmann et al., 2004]
How has ice shell thickness changed with time?

Pappalardo et al., 1999
Summary

• Multiple lines of evidence suggest that Europa’s ice shell is likely >15 km thick

• There is ample evidence for recent liquid on Europa’s surface, but such liquid may not originate directly from Europa’s ocean

• There are probably thin portions of the ice shell; these are likely to be situated above subsurface lenses of liquid or warm ice

• Data from the Europa Clipper mission will (and a potential future Europa Lander would) constrain the structure and thickness of Europa’s shell
Backup
<table>
<thead>
<tr>
<th>Source</th>
<th>Magnitude</th>
<th>Notes/References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diurnal tides</td>
<td>&lt;~100 kPa</td>
<td>Greenberg et al. (2002)</td>
</tr>
<tr>
<td>Librations</td>
<td>Comparable to diurnal?</td>
<td>Bills et al. (this volume); Sarid et al. (2006); McEwen (1986); Leith and McKinnon (1996); Geissler et al. (1998a); Sotin et al. (this volume); Leith and McKinnon (1996); Schenk et al. (2008)</td>
</tr>
<tr>
<td>Nonsynchronous rotation</td>
<td>Several MPa</td>
<td>McKinnon (1999); Nimmo and Manga (2002); Tobie et al. (2003); Showman and Han (2004); Pappalardo and Barr (2004); Han and Showman (2005)</td>
</tr>
<tr>
<td>Polar wander</td>
<td>Several MPa</td>
<td>locally; duration ~ tens of seconds</td>
</tr>
<tr>
<td>Thermal convection</td>
<td>&lt;100 kPa</td>
<td>Hoppa et al. (1999a)</td>
</tr>
<tr>
<td>Compositional convection</td>
<td>&lt;1 MPa</td>
<td>Nimmo (2004b); Kimura et al. (2007)</td>
</tr>
<tr>
<td>Thickening of the icy shell</td>
<td>Several MPa (tensile)</td>
<td>Nimmo and Schenk (2006)</td>
</tr>
<tr>
<td>Impacts</td>
<td>TPa</td>
<td></td>
</tr>
<tr>
<td>Cycloid propagation</td>
<td>&lt;40 kPa</td>
<td></td>
</tr>
<tr>
<td>Normal faults</td>
<td>&gt;6–8 MPa</td>
<td></td>
</tr>
<tr>
<td>Band rifting</td>
<td>0.3–2 MPa</td>
<td></td>
</tr>
</tbody>
</table>

References in bold denote observationally constrained values.

**TABLE 2.** Source and magnitude of strain rates.

<table>
<thead>
<tr>
<th>Source</th>
<th>Magnitude</th>
<th>Notes/References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diurnal tides</td>
<td>$2 \times 10^{-10}$ s$^{-1}$</td>
<td>Ojakangas and Stevenson (1989a)</td>
</tr>
<tr>
<td>Opening of bands</td>
<td>$10^{-15}$–$10^{-12}$ s$^{-1}$</td>
<td>Nimmo (2004d); Stempel et al. (2005)</td>
</tr>
<tr>
<td>Nonsynchronous rotation</td>
<td>&lt;~$10^{-14}$ s$^{-1}$</td>
<td>Hoppa et al. (1999b)</td>
</tr>
<tr>
<td>Undeformed craters</td>
<td>&lt;$10^{-16}$ s$^{-1}$?</td>
<td>Assumes &lt;10% local strain and crater age of 30 m.y.; only applies to postcratering deformation</td>
</tr>
</tbody>
</table>

References in bold denote observationally constrained values.